Multi-Gigabit Data-rate Optical Communication Depicting LEO-to-GEO and GEO-to-Ground Links

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Abstract - The goal of this task is to develop key components for a technology that will enable Optical Communications to meet the data delivery requirements of the EOS (Earth Observing Spacecarft) community. Both LEO-to-GEO and GEO-to-Ground links have been considered. The data-rate goal for the LEO-GEO link is 2.5 Gigabits-per-sec (Gbps) while the goal of the GEO-Ground link is 10 Gbps using a single or four multiplexed 2.5 Gbps channels. The first year (of the two-year effort) focuses on communication link demonstration in the laboratory and detailed analysis and experimental demonstration planning for acquisition, tracking and pointing. Link analysis was used to identify the required telescope aperture sizes, beacon, and transmit laser power. Current emphasis is on a 2.5 Gbps link while the components are also being developed for a 10 Gbps data-rate link. A 2.5 Gbps link was demonstrated in the laboratory and preliminary characteristics are presented here. The breadboard utilizes a 13 cm diameter telescope as transmit aperture, simulating the LEO terminal. The receiver is a 30-cm all Silicon Carbide telescope that simulates the GEO terminal. The objective of the laboratory breadboard development is to validate the link analysis. The second year of the effort would concentrate on experimental demonstration of acquisition, tracking and pointing between two moving platforms depicting a LEO-to-GEO link.

1. INTRODUCTION

It is anticipated that the next generation of remote sensing spacecraft (mostly in LEO orbit) will gather enormous quantities of data . Enabling availability of this data to ground scientists in near real time is a formidable challenge. The technology to stream the data from space to ground along with that required for buffering and ground network distribution must be addressed. The work presented here emphasizes the use of optical communications as a viable and attractive technology for meeting the former requirement, namely streaming data from space based sensors to ground stations in near real time. Using GEO relay satellites is the favored strategy for transferring large data volumes from space to ground for reasons elaborated below. It will be possible to relay such data to the ground advantageously, at the rate of multiple-Gbps, by using a lasercomm relay terminal located on Geo-stationary (GEO) relay spacecrafts. Direct detection is considered only. For LEO-GEO link, coherent detection is a very viable option since no is atmosphere present in the link medium.

The high-data-rate laser-communication technology can uniquely enable the required relay of data volumes, largely due to the following features:

- Availability of very large and unregulated bandwidths at optical frequencies
- The legacy of fiberoptic communication system technologies that now routinely operates in global telecommunications links at 1-10 Gbps data-rates. Much of this technology is directly pertinent to the free-space lasercomm systems

LEO-to-GEO CROSSLINK

LEO-GEO links are of interest since atmospheric effect (such as cloud cover) induced link availability may be mitigated. From a single ground-based receiver station, a LEO spacecraft is typically observable for less than 15 minutes in a 24-hour period. Even sites with favorable atmospheric visibility typically display a 65 to 70% availability. By contrast the line-of-sight (LOS) to a GEO terminal is maintained nearly continuously. Moreover, in the event of sustained cloud cover, the data may be re-broadcast or transmitted to a second ground receiver located within the GEO satellites LOS but in a diverse weather cell that does not have simultaneous cloud cover. Analysis shows that site diversity can increase availability fro 65-70% to >95%.

Architecture - The acquisition, tracking and pointing (ATP) architecture for the JPL-developed OCD (Optical Communication Demonstrator, shown on Figures 1 & 2) is a simple yet scalable architecture that can be adapted for the LEO-GEO cross-links being discussed and is adapted for the remainder of this study.

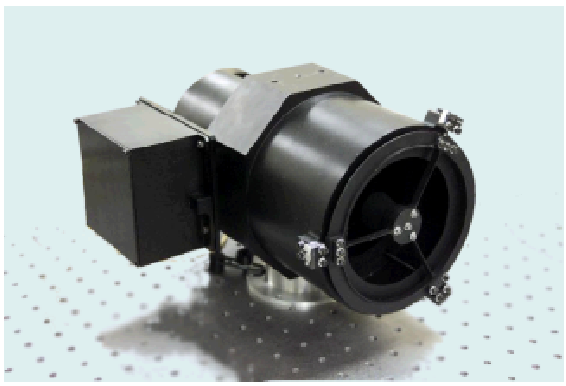


Fig. 1. Picture of the JPL-developed Laser-Communication Terminal

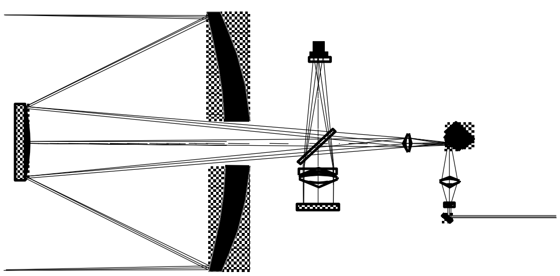


Fig. 2. Schematic Layout of the OCD terminal showing the optics, laser transmitter beam, fine-pointing mirror and focal plane array (for ATP).

ACQUISITION & TRACKING

The most challenging aspect of establishing the communication link is the ATP. Various scenarios for ATP between LEO and GEO spacecrafts are discussed. It is assumed that the computers onboard each spacecraft initiate the normal acquisition between the lasercomm system elements, utilizing previously defined clock and position references. Use of GPS and inertial navigation systems (INS) based reference system will aid the acquisition process by providing the LEO spacecraft precise knowledge of its position at all times.

For a given spacecraft, the following factors contribute to the magnitude of location knowledge (position in orbit) uncertainty:

- The spacecraft stabilization technique (3-axis, reaction wheels, spinner…);
- Quality of inertial measurement sensors (gyros, star-sensors…);
- Attitude control system;
- Attitude estimation software; and
- The disturbance environment to which the lasercomm payload is exposed.

All of these directly affect the attitude or orientation of the laser communication transceiver instantaneous line-of-sight (LOS) relative to the acquisition uncertainty cone. For purposes of communication, acquisition is defined as the time required for LEO-terminal to receive tracking data and lock-on to the beacon broadcast from the GEO-terminal. A proposed acquisition technique for inter-satellite links typically begins with one of the terminals, for example the LEO terminal, turning on a beacon for the second terminal (for example the GEO-terminal) to detect and lock onto. Thus, the GEO-terminal acquires the beacon from LEO-terminal. The requirements on the beacon pointing are that it successfully illuminates the GEO-terminal. This may be done with a beacon that instantaneously fills the entire angular error volume associated with the location of the GEO-terminal relative to LEO-terminal, or it may be done with a smaller beam that scans the error volume. Another possibility is a beacon at the GEO orbit only and no beacon on the LEO terminal. It is possible for the communication laser itself to serve as the beacon also. However, some beam broadening (defocus) may be required. The complexity of a scanning technique is avoided if the error volume is small enough so that the beacon can provide an adequate power density over the entire volume, thus providing for a good signal to GEO-terminal to detect the incoming beacon (most likely difficult to accomplish). It is possible that the LEO-terminal beacon cannot fill the entire error volume of the GEO-terminal detector field-of-view (FOV). In that case, both terminals will have to scan their beacon beams within their respective error volume. Typically, there is a finite amount of time available to perform the acquisition process. In certain acquisition scenarios both terminals may be transmitting and receiving, simultaneously. For the experiments conducted so far, it is assumed that the ATP subsystem has performed its task and has accurately pointed the two terminals together. Extensive work is underway for experiments that depict ATP between LEO and GEO spacecrafts. The work described here concentrates on the communications aspects of the link.

COMMUNICATIONS

Some of the key parameters for communications are: required data rate, bit-error-rate (BER). Various internal and external noise sources in the receiver contribute to the bit error. BER is typically driven by the average/peak signal power and RMS noise power during a bit interval. For most Earth Observing spacecrafts, a data-rate of 1 Gbps will be adequate for the LEO-to-GEO link. However, optical communication can provide 2.5 Gbps without much additional complexity since the bulk of the work is in acquisition, tracking and pointing. A data-rate of 2.5 Gbps is analyzed here and demonstrated experimentally. The required laser power may be determined by assuming the following link parameters and a link margin of 3 dB.

Wavelength:	1550 nm
Link range:	4.3E4 Km
Data-rate:	2.5 E6 kbps
BER:	1 E-7
Transmit aperture:	30 cm
Receive aperture:	30 cm

Parameter	Value	
Transmit power	3.35 W average	38.25 dBm
Transmit losses	64.5% trans.	1.90 dB
Transmittergain	(9.2 urad beam)	113.51 dB
Pointing losses		-2.01 dB
Space loss		-290.85 dB
Atmos. Losses		0.0 dB
Receiver gain		115.5 dB
Receiver losses	46% transmis.	-3.36 dB
Received signal	2570 photons/p	-30.85 dBm
Background	6.66E-9 phot./s	
Required signal	1.29E3 phot./p	-33.85 dBm
Link Margin		3.00 dB

On-off keying modulation without coding was assumed here. Inclusion of coding should increase the link margin substantially. The required average laser power of 3.25 Watt is well within the range of commercially available Er-doped fiber amplifiers (EDFAs). For higher data-rates, the transmit channel could, for example, utilize a four (4) wavelength coarse division multiplexer (CWDM). Polarization coupling provides another means of increasing the data-rate by providing an additional channel. The 1550 nm wavelength WDM technology is very well developed by fiberoptic industry. The technology of high power high-data-rate lasers at 1550 nm is maturing as well. Among other properties associated with the 1550 nm wavelength for free-space communication use is eye-safety and lower levels of background sunlight.

EXPERIMENTS

The 2.5 Gbps transmitters, receivers, electronics and characterization equipment were assembled to validate the functionality of each component. Optics (telescopes and multitude of lenses and mirrors) were assembled onto their respective breadboards. A 13 cm diameter telescope was used in the transmitter optical assembly and was individually aligned using a Zygo interferometer. An all-Silicon-carbide telescope with a 30-cm aperture was used in the receiver system. Optical throughput (transmission) of the each component was measured upon integration with the telescopes. A modulated laser transmitter was integrated with the 13-cm telescope and a high bandwidth receiver was integrated with the 30-cm telescope.

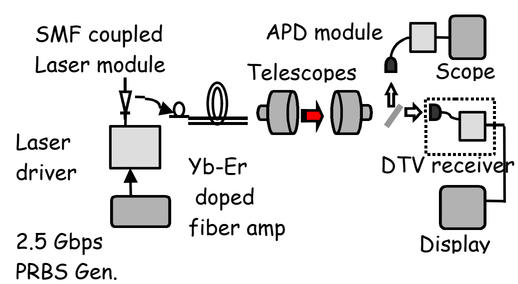


Fig. 3 Schematic of experiment

An optical link was established across an optical table while the laser transmitter was modulated up to a maximum of 2.5 Gbps. In the laboratory, a fraction of a milli-Watt (mW) of laser transmit power is sufficient to establish a link. However, to simulate the final system, an optical amplifier, capable of providing 2 W of laser power at 1550 nm, was attached to our laser transmitter and attenuated to obtain the required power levels at the receiver. Bit-error-rate testers and high- speed oscilloscopes were used to measure the BER (bit error rate) and to observe eye patterns. A clock and data recovery (CDR) unit was also used in the receiver system. Eye patterns reveal the quality of modulation and potential sources of errors as the received power is decreased.

During these tests it is assumed that the acquisition, tracking and pointing (ATP) subsystem has performed its task and has pointed the two terminals together successfully. Our goal is to experimentally match, as closely as possible, the link performance predictions assuming measured and known characteristics of the components utilized in the end-to-end link. Sample experimental data on the characterization of different transmitters, the amplified transmitter, and different receivers is shown in Fig. 4 through 10. Fig. 11 and 12 are pictures of the current setup.

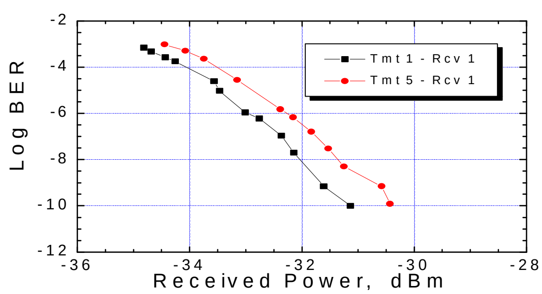


Fig. 4. BER as a function of received power at 1.4 Gbps for an APD based receiver with external CDR.

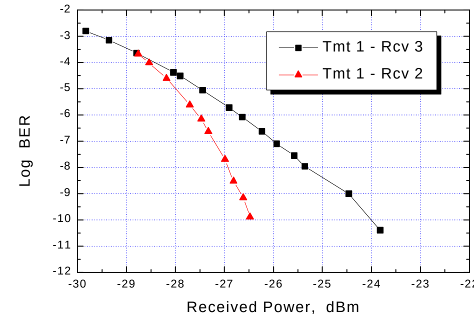


Fig. 5. BER as a function of received power at 1.4 Gbps for different PIN based receivers with external CDR. Receiver 2 is an HDTV receiver module.

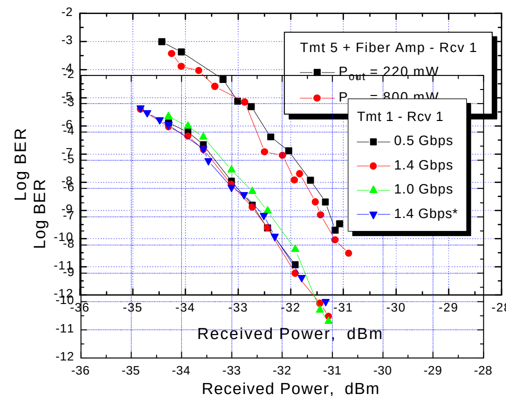
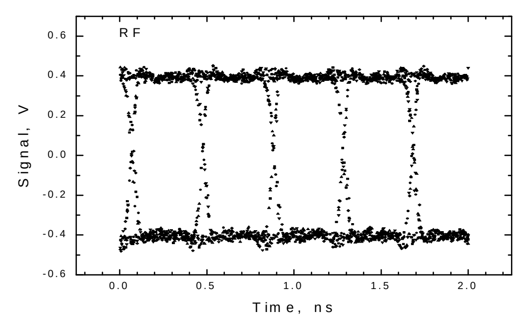


Fig. 6. Data rate dependence of BER as a function of received power for an APD based receiver with external CDR.

Fig. 7. BER as a function of received power at 1.4 Gbps for an APD based receiver with external CDR.



A transmitter is coupled through the fiber amplifier for varying pump intensities.

Fig. 8. Eye diagram of RF source modulation to transmitters at 2.5 Gbps.

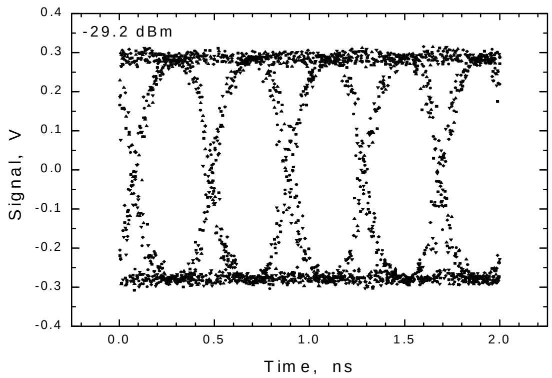


Fig. 9. "Eye diagram" for Transmitter 1 to Receiver 1 at 2.5 Gbps. Output is directly from the receiver without CDR to reveal the quality of modulation at low BER (w/ -29 dBm of input signal).

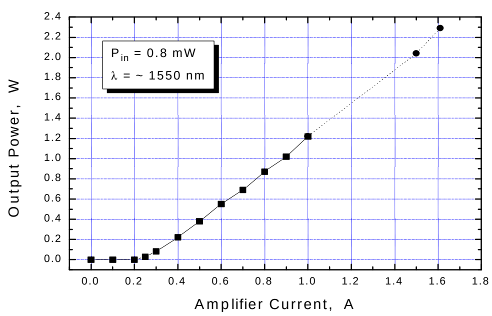


Fig. 10. Fiber amplifier output power as a function of the pump diode current. The fiber amplifier is capable of greater than 2 W average power with a channel bandwidth of 40 nm around 1550 nm.

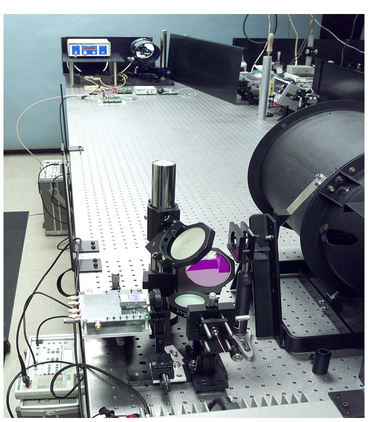


Fig. 11. A picture of the setup showing the two telescopes and associated transmitters and receiver.

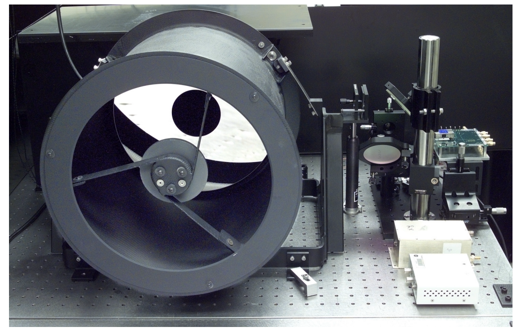


Fig. 12. A picture of the 30-cm all SiC telescope and associated receiver optics and electronics.

Measured throughput power of the laboratory optical system, which includes non-optimized optics and coatings in each of the receive and transmit telescopes, is approximately 21 % compared to 27 % used in the theoretical link analysis. The required received signal is also within 1-2 dB of that predicted by the link analysis. Thus the preliminary setup demonstrates the feasibility of the predicted links.

Acknowledgements

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